



Comparison and parameter optimization of a two-stage thermoelectric generator using high temperature exhaust of internal combustion engine



Xingyu Liang^a, Xiuxiu Sun^a, Hua Tian^{a,*}, Gequn Shu^a, Yuesen Wang^a, Xu Wang^b

^a State Key Laboratory of Engines, Tianjin University, Tianjin 300072, China

^b School of Aerospace, Mechanical and Manufacture Engineering, RMIT University, Bundoora, Victoria 3083, Australia

HIGHLIGHTS

- Presents a mathematical model of two-stage TEG.
- The contrasted of the single- and two-stage TEG.
- Effects of temperature and heat transfer coefficients of two sides of TEG.
- Effects of total number of thermocouples.
- Exists a right ratio of pairs of thermocouples in top stage to bottom stage which makes the performance of TEG optimum.

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ABSTRACT

A technical method of recovering exhaust heat in internal combustion engine (ICE) is the thermoelectric generator (TEG), which contributes to efficiency improvement. In this study, a two-stage thermoelectric model is built using the exhaust gas of ICE as heat source. After comparing the single- and two-stage TEG, we select the latter to be optimized by analyzing the effect of relevant factors. The results show that the absorbed heat, output power, and conversion efficiency increase significantly with increasing heat transfer coefficient up to the value of $400 \text{ W m}^{-2} \text{ K}^{-1}$. The effect of heat source temperature is greater than that of the cold source. Meanwhile, both output power and absorbed heat increase with increments of the total number of thermocouples, whereas conversion efficiency decreases. Finally, output power and conversion efficiency exhibit a peak value with the variation of the thermocouple ratio. The two-stage TEG achieves maximum output power when the ratio is between 0.8 and 0.9.

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1. Introduction

With the decreasing of the oil, energy saving and emission reduction of the automotive have been attracted. Thermoelectric generators can save energy costs and reduce the environment burden [1]. 55–77% (diesel engine) [2] or 70–80% (gasoline engine) [3] of fuel energy in automotive are discharged into the environment in the form of waste heat, with the heat contained in exhaust gas accounting for the major part, which can exceed 50% [4]. If the waste heat contained in exhaust gas could be effectively reutilized, engine thermal efficiency would be improved significantly.

Using the analytical network process, Liang et al. [5] concluded that among all existing waste heat recovery technologies, the thermoelectric generator (TEG) was the most promising method for recovering ICE waste heat in the future. Birkholz et al. [6]

conducted an experiment to recover heat by TEG, and the results showed that 90 thermocouples made of FeSi_2 could recover 58 W when the temperature difference was 490 K. Nissan Motor Company applied an advanced-type thermoelectric module to gasoline engine vehicles to recover exhaust heat, which could recycle 11% exhaust heat under the climb mode at a speed of 60 km h^{-1} [7]. Hi-Z Technology detailed the design of a 1.5 kW TEG laboratory prototype unit in 1984 [8]. With funding from the United States Department of Energy, Hi-Z also conducted a study on TEG using exhaust gas as heat source for truck diesel engines. The 72 integrated and improved HZ-14 thermoelectric generator modules (TEMs) can produce 1 kW power at 30 V DC during nominal engine operation [9]. The TEG developed by General Motors, which can generate 350 W for the FTP conditions, can improve fuel economy by almost 3% [10]. These studies show that with the advantages of not having mechanical moving parts and no friction, as well as quiet operation, high stability, and being environment friendly,

* Corresponding author. Tel.: +86 15822683137; fax: +86 02227404741.

E-mail address: thtju@tju.edu.cn (H. Tian).

Nomenclature

Abbreviation

TEG	thermoelectric generator
ICE	internal combustion engine
TEM	thermoelectric module

Symbols

Q	the absorbed heat (W)
P	output power (W)
T	temperature (K)
R	resistance (Ω)
R_L	external resistance (Ω)
K	thermal conductance ($W K^{-1}$)
ZT	thermoelectric figure of merit
I	current (A)
M	the total number of thermocouples
m	number of thermocouples in top stage
n	number of thermocouples in bottom stage
U	voltage (V)

l	length of thermocouple (m)
A	cross sectional area of thermocouple (m^2)

Greek letters

η	conversion efficiency (%)
α	Seebeck coefficient ($V K^{-1}$)
λ	thermal conductivity ($W m^{-1} K^{-1}$)
ρ	electric resistivity (Ωm)

Subscript

1	top stage
2	bottom stage
3	medium layer
P	P leg of thermocouple
N	N leg of thermocouple
h	heat source
c	cold source

TEG has become a viable research direction for ICE waste heat recovery.

Most studies on the TEG system have focused on model optimization [11–17], geometric parameter of thermocouple [18–20], heat exchanger [21,22], material [23,24], and new TEG structure [25,26]. Kim [15] proposed an experimental method to study the relationship between the Seebeck coefficient and temperature difference of TEG to optimize the TEG mode. Sahin and Yilbas [19] found that when high conversion efficiency of the device was required, decreasing and increasing the shape parameter would be favorable; however, when high power output was required, the shape parameter should be set to zero, which would correspond to the rectangular leg geometry. Meanwhile, increasing both heat transfer area and heat transfer coefficient can improve TEG performance [22]. Anatyckuk and Kuz [24] determined which materials were most suitable for the heat recovery of ICE. Numerous new ideas have been proposed to improve TEG performance. Shu et al. [26] proposed TEG combined with organic Rankine cycle

to recover the waste heat of ICE. The low ZT value serves a key role in the resulting low conversion efficiency. Riffat and Ma [27] highlighted that the efficiency of TEG is approximately 5% in general, and the main reason it cannot exceed 10% is that the ZT value cannot be increased effectively. Integrating the exhaust waste heat and the ordinary material into a TEG system to improve the engine efficiency has always been a significant topic.

Fig. 1 shows the exhaust temperature of a diesel engine tested by our laboratory. As shown in this figure, the exhaust temperature is about 523 K when operating on low engine load and exceeds to 813 K on high load. Many experiences can also illustrate that the exhaust has high temperature [1,28]. There is a large temperature difference between heat source and cold source when the TEG is used to recover the exhaust heat. The ZT value changes greatly in this high temperature of heat source and large temperature difference conditions (Fig. 2) [23]. That is to say: the ZT value of these two thermoelectric materials is higher than that of the single material under the same boundary conditions. So, a new high-efficiency two-stage TEG is proposed in this paper. Numerous studies have been conducted on the two-stage thermoelectric cooler [29,30]. Although the models for thermodynamic analysis are different, the researches of two-stage thermoelectric cooler can give directions on the research of TEG. Xiao et al. [31] compared

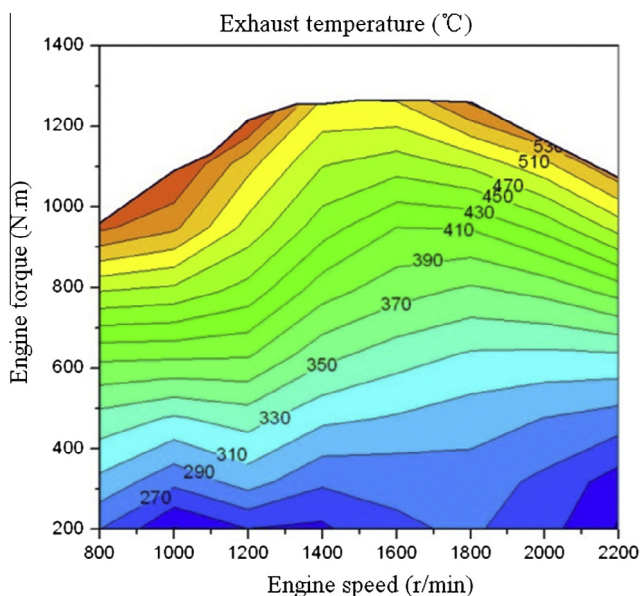


Fig. 1. Exhaust gas temperature.

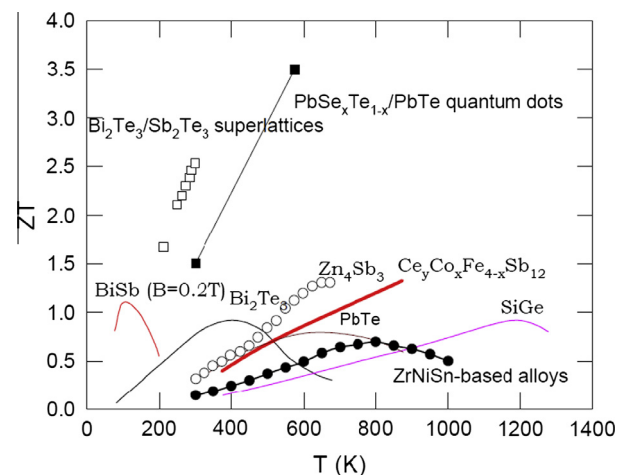


Fig. 2. The relationship of ZT value with thermoelectric material [23].

several types of TEG, such as single-stage, two-stage, and three-stage TEG, using solar energy as heat source. Dai et al. [32] conducted an experiment on serial TEG with two different kinds of material modules as the top and bottom layers. The TEG efficiency does not exceed 2% using the second conversion liquid metal as transient heat source. In this study, a new TEG structure was compared with traditional structures, and then the performance of two-stage TEG using engine exhaust as heat source was discussed by analyzing the influence of heat transfer coefficient and temperature of heat and cold sources, as well as the effect of the number of thermocouples on output work, absorbed heat, and conversion efficiency. The optimum configuration of a basic two-stage TEG was studied in detail. According to the analysis, the best performance of the two-stage TEG is determined, which may provide guidance in the design and application of two-stage TEG in ICE.

2. System description

A schematic of two types of TEG with an external resistance (R_L) is presented in Fig. 3. TEG is composed of a number of TEMs in

different forms: serial, parallel, or combination. To simplify the analysis, TEG consists of one TEM. Unlike the single-stage TEM (Fig. 3b), the two-stage TEM consists of m pairs of thermocouples on the top layer and n pairs of thermocouples on the bottom layer, which are connected with a serial wire (Fig. 3a). The total number of thermocouples of the two-stage TEG is M , i.e., $M = m + n$. The value of m and n could be the same, mainly depending on the working requirement. A thermocouple is composed of P -type and N -type semiconductor legs joined by a thin copper. Insulating ceramics on the two sides of the top and bottom of the TEM have excellent thermal conductivity.

3. Mathematical model of two-stage thermoelectric generator

3.1. Governing equations

A new method has been put forward to recover exhaust heat in this paper. The preliminary discussion on performance of two-stage TEG has been researched in the steady state of ICE. The exhaust gas and coolant flow from the surface of two-stage TEG.

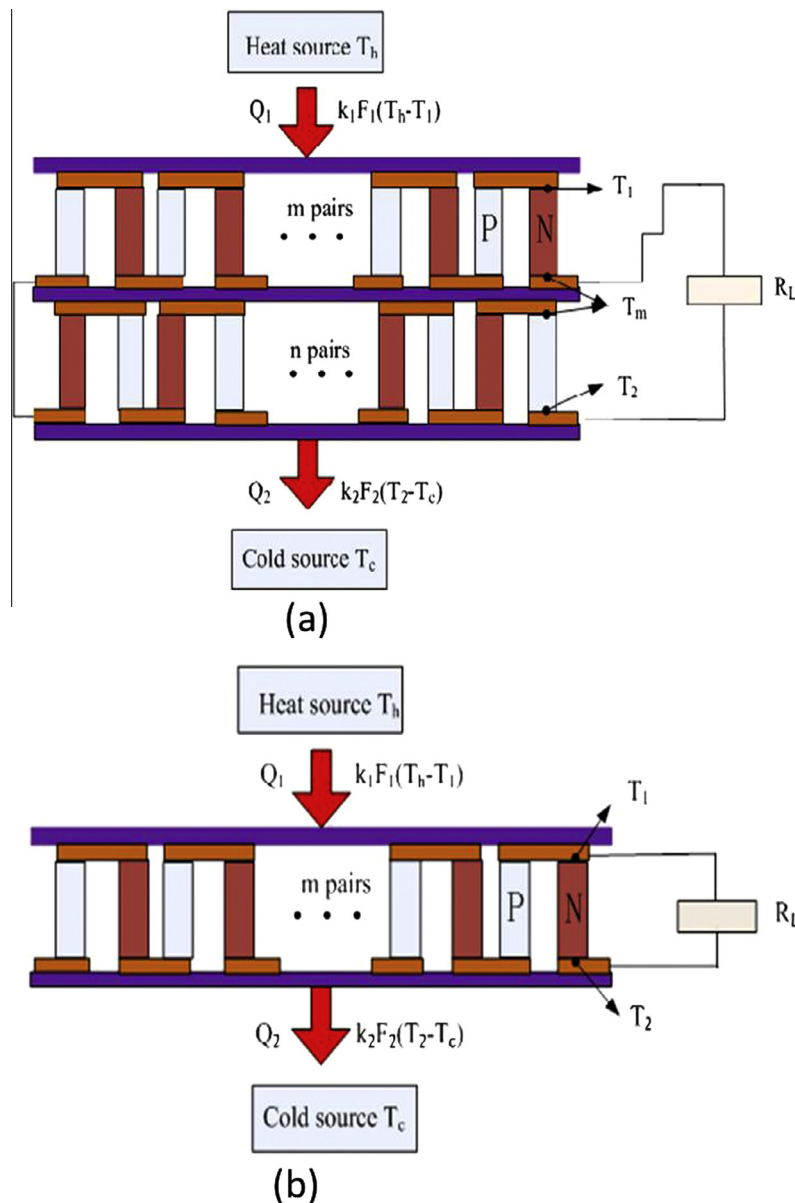


Fig. 3. A schematic diagram of two kinds of TEG: (a) two-stage TEG and (b) single-stage TEG.

The heat is transferred from the heat source at temperature of T_h , and released at temperature of T_c . A part of the absorbed heat is transformed into electricity through two-stage TEG in this process. The form of the two-stage TEG is electric in serial and thermal in parallel. The size of TEM is so small that the temperature difference for the thermocouples in TEG is negligible. Several assumptions are made as follows:

1. The thermal conductivity, electrical conductivity, and Seebeck coefficient of the material changes with the average temperature of the two sides of the thermocouple.
2. Both the thermal and flow are steady.
3. The temperature of the low-temperature end of the top stage is the same as that of the high-temperature end of the bottom stage.
4. Thermal contact resistance is ignored.
5. Heat conduction flows along the direction of the thermal couple leg, and both the heat conduction in the axial direction and radiation heat are neglected.

Let's Q_1 represent the heat that absorbed from its heat source by the TEM, and Q_2 represent the heat that released to its cold source. k_1F_1 and k_2F_2 are the thermal conductance in the heat and cold sides, where k_1 , F_1 , k_2 , F_2 are thermal transfer coefficients and thermal transfer surface respectively.

According to Newton cooling law, Q_1 and Q_2 can be expressed as:

$$Q_1 = k_1F_1(T_h - T_1) \quad (1)$$

$$Q_2 = k_2F_2(T_2 - T_c) \quad (2)$$

The heat absorbed by the two-stage TEG consists of Peltier heat, thermal conduction, and Joule heat, whereas the heat generated by Thomson effect is ignored because Thomson heat is negligible. The generated Joule heat is distributed homogenously on the two sides of the thermocouple. So Q_1 can also be expressed as:

$$Q_1 = \left(\alpha_1 IT_1 - \frac{I^2 R_1}{2} + K_1(T_1 - T_3) \right) m \quad (3)$$

Similarity, Q_2 can also be expressed as:

$$Q_2 = \left(\alpha_2 IT_3 + \frac{I^2 R_2}{2} + K_2(T_3 - T_2) \right) n \quad (4)$$

In the processing of heat transferred, the heat from the top stage of TEM can be moved to the bottom stage in the same quantity according to the assumption. Let Q_3 represent the heat that released to the bottom stage. From the top stage of TEM perspective, Q_3 can be expressed as:

$$Q_3 = \left(\alpha_1 IT_3 - \frac{I^2 R_1}{2} + K_1(T_1 - T_3) \right) m \quad (5)$$

Q_3 can also be derived from the aspect of the absorbed heat in the bottom stage, so it can be expressed in another way.

$$Q_3 = \left(\alpha_2 IT_3 - \frac{I^2 R_2}{2} + K_2(T_3 - T_2) \right) n \quad (6)$$

where I is the current flowing in the TEM. The thermocouples of the two-stage TEM are arranged serially, so the current in the two stages is the same. Thus, the equation of the current is expressed as follows:

$$I = \frac{mU_1 + nU_2}{mR_1 + nR_2 + R_L} = \frac{m\alpha_1(T_1 - T_3) + n\alpha_2(T_3 - T_2)}{mR_1 + nR_2 + R_L} \quad (7)$$

A thermocouple is treated as a unit based on this assumption. The properties of P -leg and N -leg depend on the average temperature of the individual materials. The materials of the top and bottom stage are different in this study. So the property of a PN unit at the top and bottom stages is described as follows [33]: α , K , R are represented Seebeck coefficient, thermal conductance and internal resistance respectively.

$$\alpha_1 = \alpha_{P1} - \alpha_{N1} \quad K_1 = \frac{\lambda_{P1}}{l_{P1}} A_{P1} + \frac{\lambda_{N1}}{l_{N1}} A_{N1} \quad R_1 = \frac{\rho_{P1}}{A_{P1}} l_{P1} + \frac{\rho_{N1}}{A_{N1}} l_{N1} \quad (8)$$

$$\alpha_2 = \alpha_{P2} - \alpha_{N2} \quad K_2 = \frac{\lambda_{P2}}{l_{P2}} A_{P2} + \frac{\lambda_{N2}}{l_{N2}} A_{N2} \quad R_2 = \frac{\rho_{P2}}{A_{P2}} l_{P2} + \frac{\rho_{N2}}{A_{N2}} l_{N2} \quad (9)$$

T_3 represents temperature of the intermediate layer, which can be got from combining Eqs. (5) and (6). So, T_3 is obtained as shown in Eq. (10).

$$T_3 = \frac{1}{2} \frac{mI^2 R_1 + 2mK_1 T_1 + nI^2 R_2 + 2nK_2 T_2}{mK_1 + nK_2 + n\alpha_1 - m\alpha_2} \quad (10)$$

The expression of T_3 is input into Eqs. (1)–(3), (and) (6) so that T_1 and T_2 can be derived through these formulas by MATLAB. The output power and conversion efficiency of the two-stage TEG can then be determined. The output power (P) and conversion efficiency (η) are presented in Eqs. (11) and (12).

$$P = Q_1 - Q_2 \quad (11)$$

$$\eta = P/Q_1 \quad (12)$$

3.2. Thermoelectric material properties

Different materials are used at the stages of two-stage TEG. The exhaust temperature fluctuate around 700 K, $(\text{Zn}_{0.9975}\text{Ge}_{0.0025}\text{Sb}_3)$ [34], and $\text{Ba}_{0.4}\text{In}_{0.4}\text{Co}_4\text{Sb}_{12}$ [35] have higher ZT value than others around this range of temperature, so which are used as P -leg and N -leg at the top stage. Bi_2Te_3 [36], which is applied in HZ-20, is used at the bottom stage because it exhibits better performance at low temperature. The thermal conductivity, electrical resistance, and Seebeck coefficient of the thermoelectric material used in this study are listed in the references. They are varied with the change of temperature. Table 1 lists the parameters for PN materials used in the present paper.

3.3. Boundary conditions

The other parameters such as the temperature of exhaust and the coolant are listed in Table 2. The temperature of exhaust and coolant varies. The assumption temperatures lie in these ranges when the effect of temperature of heat and cold source is researched on the performance of two-stage TEG. 500/800 K is also in the range of exhaust temperature when the effects of other aspects are researched. So, these values are reasonable assumption. The values of heat transfer coefficient are also assumed in the range of changing. These values are reasonable for researching the performance of two-stage TEG in steady state. In other subsequent analysis without special description, the parameters are taken from these tables. The materials used for the two-stage

Table 1
Parameters of PN materials.

Parameters	Top stage		Bottom stage	
	P	N	P	N
Height l (m)	0.003	0.003	0.003	0.003
Sectional area A (m ²)	0.00248	0.00248	0.00248	0.00248

Table 2

Other parameters.

Exhaust gas temperature (K)	500/800
Cooling water temperature (K)	353.15
Heat transfer coefficient in hot side ($\text{W m}^{-2} \text{K}^{-1}$)	800
Heat transfer coefficient in hot side ($\text{W m}^{-2} \text{K}^{-1}$)	1000
Heat transfer area (m^2)	0.005625
Ratio of external resistance to internal resistance	1

TEG are also used in the single-stage TEG to comparison. The contrast between the single- and two-stage TEG is detailed in the following section.

4. Validation

Numerical results are validated by comparing the value of power and conversion efficiency with that in the research of Chen et al. [25]. The materials are the same at both stages, and the property of the material is set as a constant at different temperatures. For example, the Seebeck coefficient is $2.3 \times 10^{-4} \text{ V K}^{-1}$ and the total internal electrical resistance of the thermocouple is $1.4 \times 10^{-3} \Omega \text{ m}$. The temperature of the heat source is 600 K, and the cold side temperature is 300 K. The transfer coefficient and heat transfer areas of the two heat exchangers are also constant. As shown in Fig. 4, good agreement is achieved between the present results and those in the research of Chen et al. [25]. Thus, the proposed model in this paper is reasonable.

5. Results and discussion

5.1. Performance comparison of single- and two-stage TEG

Figs. 5 and 6 show a comparison of output power and conversion efficiency for single-stage and two-stage TEG at different heat source temperatures. As shown in Figs. 5 and 6, the maximum output power and conversion efficiency of two-stage TEG are 18.6% and 23.2% higher than that of single-stage TEG, respectively. We can conclude that the two-stage TEG is advantageous over the single-stage TEG when the heat source temperature is between 600 K and 800 K. The external resistances are small when the output power and conversion efficiency have peak values for one two-stage TEM. However, the external resistance is adjustable as the two-stage TEG is made up of many TEMs. The property of material causes the ZT value for skutterudite to be lower than that of Bi_2Te_3 when the average temperature of the two sides of the thermocouple is low. We can predict that the two-stage TEG can exhibit satisfactory performance using exhaust gas as heat source. The

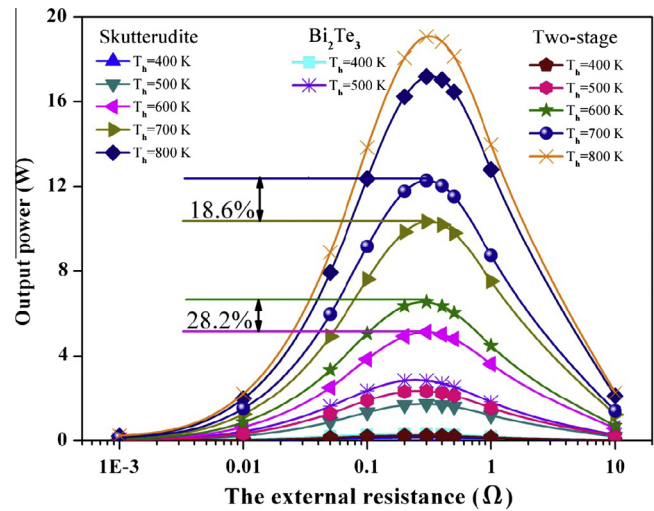


Fig. 5. The comparison of output power of single- and two-stage TEG.

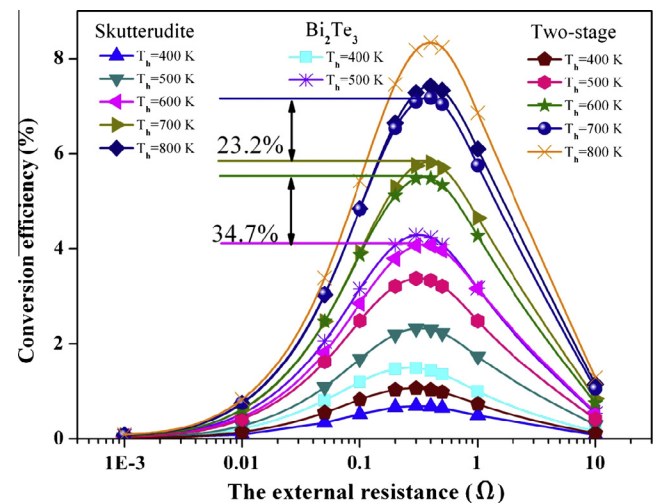


Fig. 6. The comparison of conversion efficiency of single- and two-stage TEG.

research of the two-stage TEG provides a new way to waste heat recovery for internal combustion engine. If ten percent is the target for improving the conversion efficiency of TEG. It is more easy to come true than the single-stage TEG.

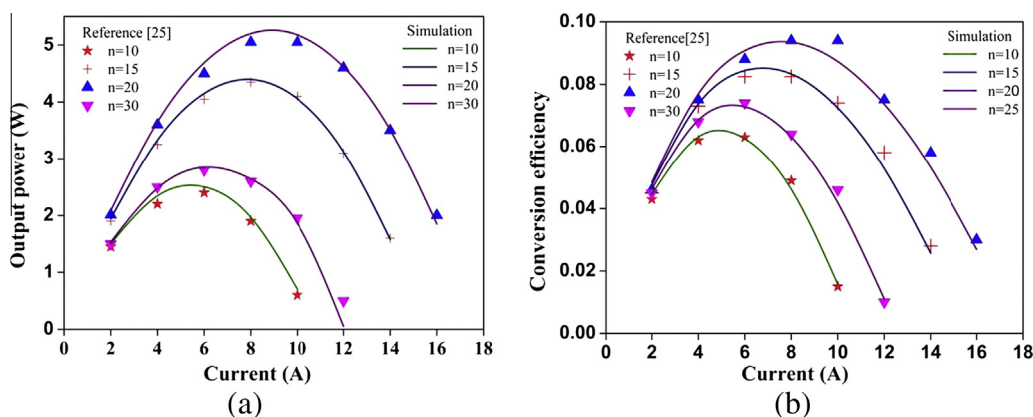


Fig. 4. Validation of the numerical model. (a) Output power and (b) conversion efficiency.

The structure of two-stage TEG seems that two kinds of single-stage TEG overlay. So it is not complicate. The advantages of single-stage TEG are also embodied in two-stage TEG. That is to say: the two-stage TEG is reliability and feasibility. Although the cost of two-stage TEG is higher than the single-stage TEG, the efficiency is also higher. If the heat exchanger is optimized, the pressure drop of exhaust turns small when it crosses the heat exchanger, which is showed by experiment in our lab. It is possible to install the two-stage TEG on the exhaust pipe. Above all, the two-stage TEG has more potential to improve the thermal efficiency of ICE by these comparisons. Thus, the performance of the two-stage TEG should be analyzed in detail.

5.2. Effects of heat and cold source temperature

Fig. 7 indicates the variation of absorbed heat, output power, and conversion efficiency at different heat and cold source temperatures. The performance will be improved by increasing the temperature of the heat source, as well as by decreasing the temperature of the cooling side (see Fig. 7d). Due to the limit of temperature in cold source, the performance cannot be improved large. The effects have no relation to the value of external resistance, which can be got from others figures. However, the value of external resistance has an important effect on the performance of TEG. There is optimum value that makes output power and conversion efficiency have a maximum, which are different.

In fact, a higher temperature of the heat source causes a higher temperature difference, which causes the current of the two-stage TEG to increase. The temperature difference and current also increase with decreasing cooling temperature, but the added amount is smaller than that of the results when the heat source

temperature increases. The thermal conductivity will be improved due to the increasing of the temperature difference. Most of energy obtained from thermal conductivity. The current is directly proportional to the output power. So the output power will be increasing for the added of the current.

The performance of the two-stage TEG was mainly affected by the temperature of the heat and cold sources and could be improved by increasing the temperature of the heat source, as well as by decreasing the temperature of the cooling end. However, the effect was less prominent in the latter case. When the engine exhaust was applied as the heat source, the heat transfer coefficient of the coolant was relatively larger among the cold source media. Thus, the coolant of energy could be used as the cold source.

5.3. Effects of heat transfer coefficient of each side

Fig. 8 plots the variation of performance under different heat transfer coefficients. The absorbed heat increases evidently when the heat transfer coefficient is less than $400 \text{ W m}^{-2} \text{ K}^{-1}$. Notably, the absorbed heat influenced by k_1 becomes smaller than that caused by k_2 when the heat transfer coefficient is approximately $800 \text{ W m}^{-2} \text{ K}^{-1}$. The output power exhibits an evident increasing process with the augmentation of k_1 or k_2 . The difference between the two different output power values decreases when the heat transfer coefficient is more than $400 \text{ W m}^{-2} \text{ K}^{-1}$. When k_1 or k_2 is small, the trends of conversion efficiency and output power grow rapidly. k_1 has more influence on conversion efficiency than k_2 when the heat transfer coefficient is less than $800 \text{ W m}^{-2} \text{ K}^{-1}$.

When the heat transfer coefficient is lower than $800 \text{ W m}^{-2} \text{ K}^{-1}$, the temperature difference at the bottom stage caused by k_1 is larger than that caused by k_2 , which not only makes up for the decrease of

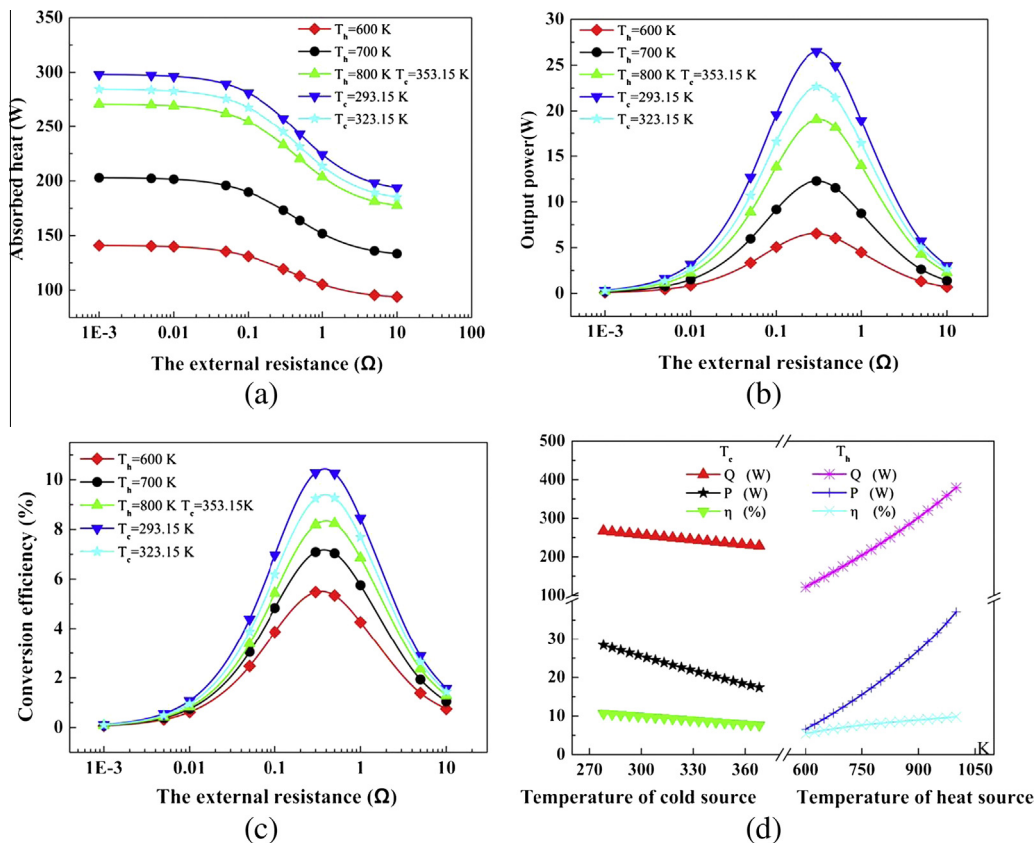


Fig. 7. Variation of performance with the temperature of heat and cold source (a) the absorbed heat, (b) the output power, (c) the conversion efficiency and (d) performance with the temperature of heat and cold source.

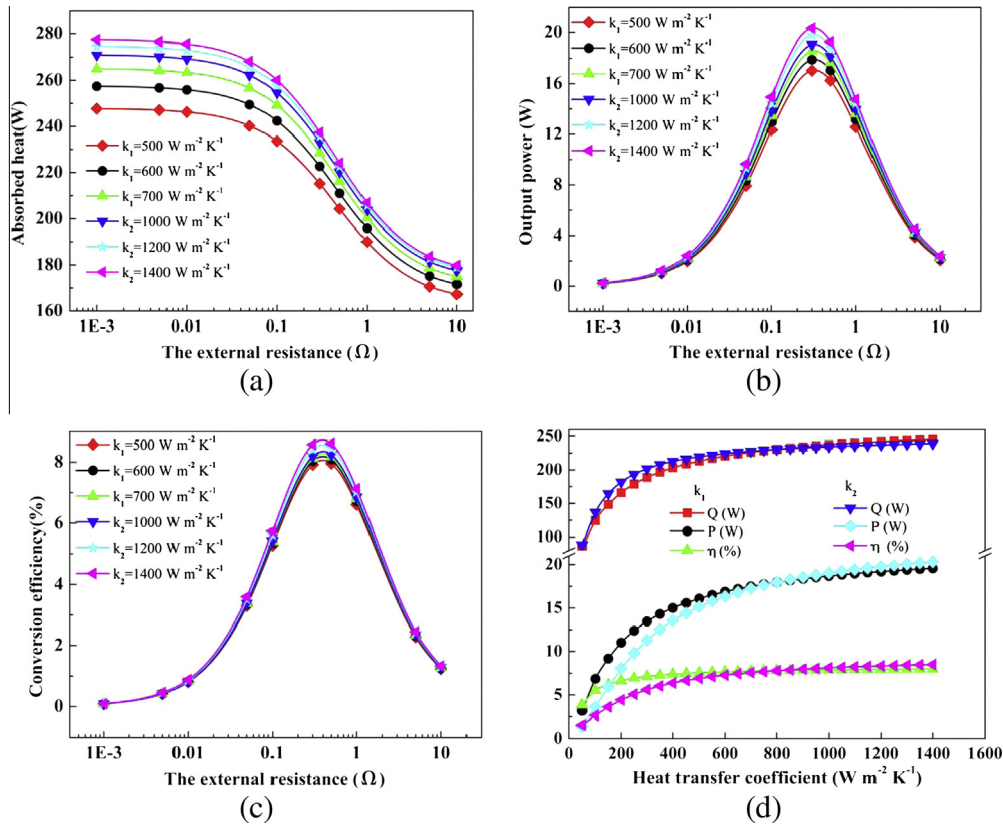


Fig. 8. Variation of performance with external resistance and heat transfer coefficient (a) the absorbed heat, (b) the output power, (c) the conversion efficiency and (d) performance with heat transfer coefficient.

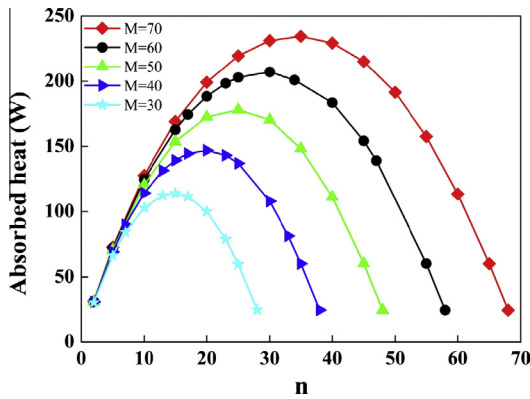


Fig. 9. Variation of absorbed heat with the total number of thermocouples.

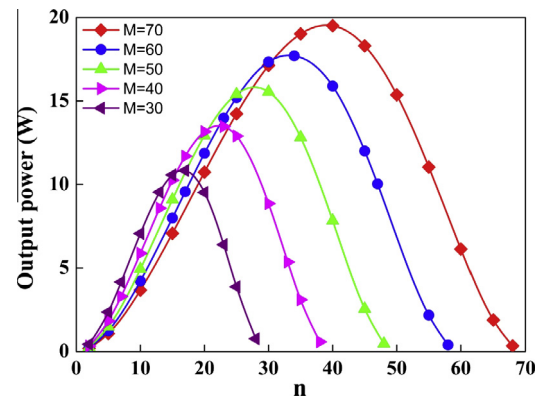


Fig. 10. Variation of output power with the total number of thermocouples.

Table 3
Value of n in the maximum of P , Q , η at different M .

M	n	P_{\max} (W)	n	η_{\max} (%)	n	Q_{\max} (W)
70	39	19.54	43	8.56	34	234.51
60	33	17.81	36	8.84	30	207.13
55	21	16.9	33	8.98	27	192.85
50	28	15.82	30	9.128	25	170.33
45	25	14.72	27	9.28	22	162.84
40	22	13.52	24	9.44	20	147.09
30	17	10.84	18	9.77	15	114.05
20	11	7.76	12	1.01	10	78.71

open circuit voltage caused by the smaller temperature difference at the top stage, but also increases the open circuit voltage of the two-stage TEG. However, when the heat transfer coefficient exceeds

$800 \text{ W m}^{-2} \text{ K}^{-1}$, the open circuit voltage is almost the same as the trend of changing k_1 and k_2 .

From Fig. 8(a)–(c), the effects of changing the heat transfer coefficient have no relation to the external resistance. However when R_L exceeds 0.1Ω , the absorbed heat decreases drastically. The output power and conversion efficiency have a peak value with the increasing of external resistance. But the external resistances are different when the output power and conversion efficiency are maximum. The external resistance plays an important role in improving the performance of two-stage TEG.

The average temperature is basically constant at the top stage, such that the values of α , λ , and ρ are almost the same, and the temperature difference only increases by approximately 30 K.

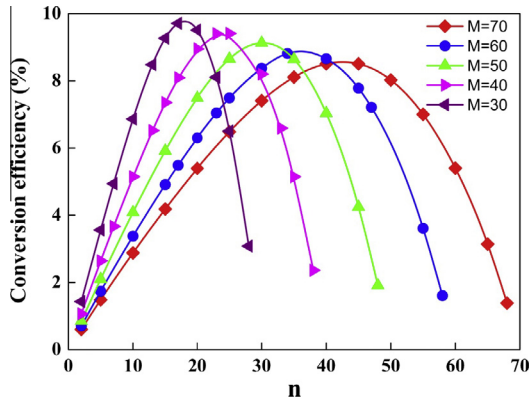


Fig. 11. Variation of conversion efficiency with the total number of thermocouples.

However, the current reduces evidently, which serves a key function in reducing Peltier heat and Joule heat, thereby resulting in a decrease in absorbed heat. The output power also decreases for the current reduce.

The value of k_2 can be easily increased by using different cold sources, but we should choose a reasonable k_1 according to the cost because the heat source is constant. This assumption can provide guidance in designing the two-stage TEG.

5.4. Effect of total number of thermocouples in the two-stage TEG

Fig. 9 plots the variation of absorbed heat with the total number of thermocouples in the two-stage TEG. An optimum n that

maximizes the absorbed heat at different M values must exist. The maximum absorbed heat increases with the increasing value of M . With the increasing of M , the temperature of thermocouples decreases in the top stage. According to the Newton cooling law, the heat absorbed from the heat source increases. And, the absorbed heat is directly proportional with the number of thermocouples. Table 3 shows the optimum value of n required to achieve the maximum of P , Q , and η at different M . According to Table 3, when n/M is 0.5, the maximum absorbed heat can be obtained.

Fig. 10 shows the effect of n on the output power at different M . With increasing M , the maximum optimum output power increases. For a fixed M , an optimum n exists. The optimum output power can be obtained when n/M is 0.56 with Bi_2Te_3 as bottom stage material (see Table 3). With increasing M , the current decreases slightly, but external resistance increases. For a fixed M , the internal resistance decreases, but the current first increases and then decreases with increasing n . The maximum current can be obtained with almost the same number of thermocouples at the top and bottom stages.

The variation of the conversion efficiency with n at different M is illustrated in Fig. 11. The maximum conversion efficiency decreases with increasing M . However, for a fixed M , an optimum n that results in the maximum conversion efficiency exists. The increasing rate of absorbed heat is larger than that of output power. Thus, conversion efficiency decreases with increasing M . For the same M value, the variation of the increasing trend of absorbed heat and output power causes a peak point of the conversion efficiency. The maximum conversion efficiency can be obtained when the ratio of n/M is 0.6 (Table 3). Therefore, a reasonable choice can be made for the optimum allocation of the number

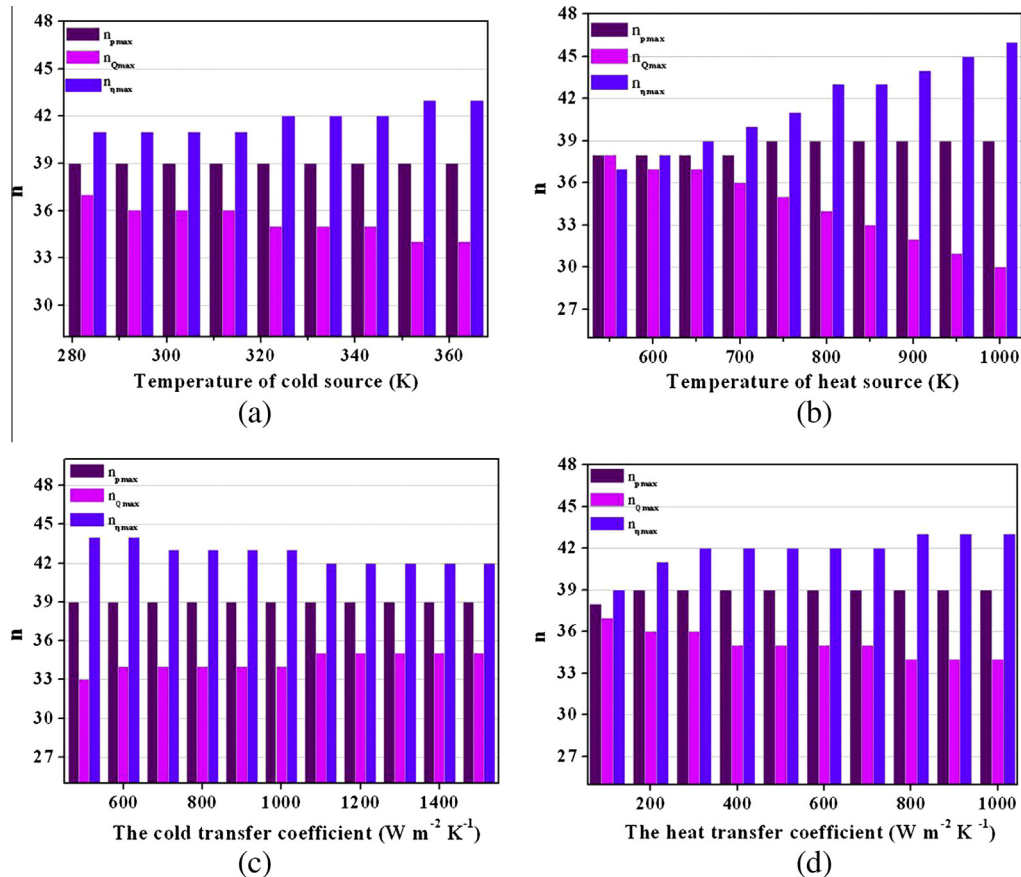


Fig. 12. The optimum value of n with different performance at different conditions: (a) temperature of cold source, (b) temperature of heat source, (c) the cold transfer coefficient and (d) the heat transfer coefficient.

of thermocouples between the top and bottom stages with different M .

The ratio of the number of thermocouples affects the performance of the two-stage TEG, and so does the number of thermocouples n . The values of n are different when Q , P , and η have the maximum value. For example, when M is 70, the maximum absorbed heat is 234.51 W. The output power and conversion efficiency at this point are 18.74 W and 7.992%, separately, which are 4% and 7% lower than the maximum output power and the maximum conversion efficiency, respectively. When the output power has a maximum value of 19.537 W, the absorbed heat and conversion efficiency are 231.032 W and 8.4563%, which are 1.5% and 1.2% lower than the maximum value of absorbed heat and conversion efficiency, respectively. When the conversion efficiency has a maximum value of 8.56%, the corresponding values of absorbed heat and output power are 221.9328 W and 18.997 W, which are 5.7% and 2.8% lower than their maximum value, respectively. We can conclude that the optimum ratio of the number of thermocouples at the top and bottom stages mainly depends on the output power, which can enhance the performance of the TEG system.

5.5. Value of n for the optimum of Q , P , and η under different conditions

Fig. 12 shows the optimum value of n to achieve the best performance under different conditions. According to Fig. 10, enabling the absorbed heat, output power, and conversion efficiency to achieve optimum value is impossible for the same n . In the simulation conditions, the output power reaches the maximum when the value of m/n is between 0.8 and 0.9. The best range for absorbed heat and the conversion efficiency are 0.8–1 and 0.6–0.9, respectively. According to our analysis, the number of thermocouples at the top and bottom stages must be designed to obtain the maximum output power. In other words, the optimum ratio of m/n should be 0.8–0.9 to achieve the best performance of the two-stage TEG. The number of thermocouples in the top and bottom stages can have a significant effect on the performance of the two-stage thermoelectric generator.

6. Conclusion

Based on Newton cooling law, as well as Fourier's and Seebeck effect, a model of a two-stage TEG was built using the exhaust gas of ICE as heat source. The performance of the generator was analyzed by simulating the effect of relevant factors. The main conclusions are as follows:

1. The output power and conversion efficiency of the two-stage TEG are higher than that of the single-stage TEG when the temperature of heat source varies from 600 K to 800 K.
2. The absorbed heat, output power, and conversion efficiency increase significantly by changing the heat transfer coefficient of the two sides, which are less than $400 \text{ W m}^{-2} \text{ K}^{-1}$. The performance of the two-stage TEG is improved by changing k_1 when the heat transfer coefficient is less than $800 \text{ W m}^{-2} \text{ K}^{-1}$. In fact, the performance does not improve significantly when the heat transfer coefficient exceeds a certain value.
3. The effect of the temperature of the heat source is greater than that of the temperature of the cold source. The use of exhaust gas as heat source requires the selection of an appropriate cold source. The coolant of ICE is a suitable cold source.
4. The output power and absorbed heat increase when increasing the total number of thermocouples, but an opposite trend is observed for conversion efficiency. With variation in the ratio of pairs of thermocouples at the top and bottom stages, the

output power and conversion efficiency exhibit a peak value. When the ratio is between 0.8 and 0.9, the two-stage TEG can achieve the best performance, during which the output power reaches the maximum level.

Based on the above conclusions, it can be draw that the two-stage TEG has great potential to recover exhaust heat of ICE. Therefore, much works has to be done to improve the performance of two-stage TEG and the research of heat transfer enhancement can be down in the future when the ICE in transient state.

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